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INFLUENCE OF HYSTERETIC DETERIORATIONS IN SEISMIC RESPONSE OF MULTISTORY STEEL FRAME BUILDINGS

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SUMMARY

This paper presents a summary of two year long comprehensive parametric study of the impact of various deterioration characteristics on seismic response of moment resisting steel structures. More than 14,000 nonlinear analyses were performed utilizing more than 500 earthquake time histories. The results indicate that various hysteretic deterioration types affect seismic demand characteristics differently. Three types of hysteretic deterioration were considered: stiffness, slip or pinching, and strength degradations.

INTRODUCTION

In order to obtain further insight into seismic demands imposed on the steel moment resistant frame buildings as designed and constructed in the various regions of the United States, a series of comprehensive analytical investigations were commissioned as a part of the Phase II of the SAC Joint Venture research program. Together these investigations formed the System Performance research effort. These individual research efforts where highly coordinated and as whole provide the most comprehensive evaluation ever of the seismic demands imposed on building structures. This paper summarizes the findings of Task 5.4.4. Briefly stated, the objectives of this task were as follows:

Assess on a consistent statistical basis the relative effect on local and global response parameters of various types of deterioration in hysteretic characteristics that might be exhibited by steel moment-resisting frames constructed with different types of connections utilizing a variety of generic details;

Identify conditions where deterioration of hysteretic characteristics has either a benign or an adverse impact on system performance or reliability relative to systems without deterioration;

Assess the need to develop beam-to-column connection details with non-deteriorating, full hysteretic loops;

Develop procedures to predict important local and global seismic demand parameters for steel moment-resisting frames exhibiting various types of hysteretic behavior, accounting for the dynamic characteristics of the structure and design ground motion; and

Evaluate and improve simple numerical elements (for a non-proprietary computer program for the analysis of structural systems) that are capable of simulating the deterioration of strength and stiffness in beams (and possibly columns) associated with material properties, local buckling, slip, fracture and other physical phenomenon.

We have considered four distinct types of hysteretic behavior:

No deterioration (i.e., bilinear behavior)

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Stiffness deterioration

Slip or Pinching deterioration, and

Strength deterioration (not covered in this paper due to space limitations)

We developed new analytical models of hysteretic behavior that allow both multi-linear and smooth representation of various hysteretic characteristics. Furthermore, we did so utilizing a black-box metaphor, so that our hysteretic models can be readily integrated into any nonlinear-capable computer program. The earthquake ground motions utilized in this study were developed as a part of the SAC Task 5.4.1 for sites in Los Angeles (Seismic Zone 4), Seattle (seismic Zone 3), and Boston (Seismic Zone 2). Detailed information regarding these suites of ground motion containing both recorded and simulated records may be found in a SAC report by Somerville, Smith, Punyamurthula, and Sun (1997).

The buildings used for parametric studies are described in detail in the SAC Task 5.4.2 report by Krawinkler and others (1998). SAC commissioned three consulting firms local to Los Angeles, Seattle and Boston to perform code designs for three, nine, and 20 story model buildings according to local prevailing code requirements. The Los Angeles and Seattle model buildings were designed according to the UBC-94 (ICBO, 1994) while the Boston model buildings were designed to comply with BOCA-93 (BOCA, 1993) requirements.

In our analyses, we have used expected yield values of 339 MPa (49.2 ksi) and 397 MPa (57.6 ksi) rather than the specified values of 248 MPa (36 ksi) and 345 MPa (50 ksi), respectively. We have also used concentrated plasticity (plastic hinge length of zero) rather than distributed plasticity in our models.

Since seismic demands imposed on systems with bilinear systems serve as the reference point for measuring the effects of deteriorating hysteretic behavior, response of structures with bilinear connection characteristics are covered first. Seismic demands imposed on systems with stiffness, slip, and strength deterioration characteristics are compared to the demands imposed on bilinear systems in subsequent sections of this paper.

One of the major difficulties in compiling this paper was condensing the sheer volume of information we had generated. We performed in excess of 14,400 nonlinear dynamic analyses. The result summaries were converted to a series of spreadsheets and charts, resulting in tens of thousands of such documents. While all this information has been submitted to SAC on several CD-ROM discs and will be shortly made available on our worldwide web site (http://www.johnmartin.com/research), there was no practical way of presenting all of this information in this paper. Consequently, we have decided to limit the scope of this paper to presentation and discussion of the effects of very severe hysteretic deteriorations to one level of seismic risk (2% probability of exceedance in 50 years) and four important seismic demand indicators, namely:

Inter-story drift ratios or drift angles.

Residual inter-story drift angles or the permanent drift angles present in the building at the end of excitations caused by earthquake ground motion.

Story shear distribution throughout the height of the structure, and

Overturning moment distribution throughout the height of the structure

We realize that this decision has left out discussion of some important seismic demand indicators such as beam and column plastic rotations. We hope, however, that the interested readers will take the time to evaluate the effect of hysteretic deterioration on the seismic demand indicators not specifically addressed in this paper by reviewing our complete set of spread-sheets and charts which will be made publicly available by SAC shortly.

THE HYSTERESIS MODELS

The monotonic load-deformation characterization is not sufficient for the inelastic seismic analysis of structures, since when a structure is seismically excited, it is loaded and unloaded, with many irregular load reversals, which take the structure to multiple excursions into the inelastic range. In order to analyze a structure close to collapse under such loading, an accurate modeling of its hysteretic behavior is required.

Hysteretic modeling of structural elements is done usually by fitting mathematical models of load-deformation relationships into experimental data from cyclic loading tests. Several such models have been developed (Mazzolani and Piluso, 1996), some of which are specific to particular materials such as reinforced concrete, steel, or visco-elastic dampers, while others are more general. All these models are based on a backbone curve with specific rules for loading and unloading.

The most popular backbone model, due to its simplicity, is the bilinear model with or without a post-yielding stiffness. However, most structural elements do not exhibit such a simple behavior. They undergo phenomena such as slip (or pinching) and stiffness and strength degradation. We present material models that account for such behavior.

The hysteretic behavior of steel structural elements had to be described adequately during our analyses. Numerous experimental results have shown that special characteristics of steel could not be successfully described from the existing hysteretic models originally designed for concrete elements. Such characteristics are the Bauschinger effect, the bilinear behavior (commonly used for analysis of steel structures) or the complex types of strength deterioration.

An additional reason was that from a programming point of view, the existing hysteretic model required quite a lot of 'housekeeping'. The new hysteretic model is created in such a way that it is simple and computationally efficient. The 'black box' approach used here gives great versatility to the model and the possibility for it to be incorporated in many structural analysis programs.

Two different models are developed; one based on a mechanical concept (referred as 'multi-linear' from this point on) and one using a mathematical perspective (referred to as 'smooth'). A basic characteristic of both models is their versatility. The models can be driven by using either force or displacement increments. By keeping track of the response history, when a new force/displacement increment is applied, the resulting displacement/force increment and the new tangent stiffness are returned as result. A new feature introduced is the capability of our models to reduce the section strength to zero. This gives us the opportunity to introduce a failure analysis procedure that can simulate the brittle failure that many steel 'beam to column' joints experienced during the 1994 Northridge earthquake.

PARAMETER MATCHING

In order to verify the adequacy of our hysteretic models, we performed analytical simulation of 12 experimental tests conducted by various SAC researchers. In each case appropriate degradation parameters were selected to best fit the observed experimental results. In all cases our hysteretic models showed that they could be used to accurately reproduce test results. As an example, the simulation of SAC experiment with test ID of EERC-RN2 (SAC, 1996) is presented here. This is a specimen with a top and bottom triangular beam haunch where beam flange was not welded and during the test flange local buckling and web distortion occurred. The hysteresis loops obtained during the test and generated by our analytical model are compared in Fig. 1.

EFFECTS OF STIFFNESS DETERIORATIONS

We evaluate the effects of severe stiffness deterioration on seismic demand by comparing the demands imposed on systems with stiffness deterioration characteristics to those imposed on similar but non-deteriorating systems. For the sake of brevity, in the rest of this paper we refer to categories of earthquake ground motions as Level I, Level II, and Level III events. Level I events are those with 50% probability of exceedance in 50 years or an average return period of 72 years. Level II events correspond to a 10% probability of exceedance in 50 years or an average return period of 475 years. Level III events represent a 2% probability of exceedance in 50 years or an average return period of roughly 2,000 years.

Severe stiffness deterioration resulted in the collapse of the Model Los Angeles 20-story building when subjected to three simulated ground motions that represent a Level III event. No other collapses due to stiffness deterioration were observed.

The Three Story Buildings

Los Angeles, California. The effect of stiffness deterioration on story shear and overturning moment demands were negligible. Severe stiffness degradation increased the median interstory drift angle by about 20% for Level I events, 40% for Level II events, and 80% for Level III events. The corresponding 84th percentile story drift angles have increased by 40%, 70%, and 110%, respectively. Severe stiffness deterioration can increase the residual interstory demand (the permanent out of plumpness at the end of excitation) by as much as 125%.

Seattle, Washington. Here again the effect of stiffness deterioration on story shear and overturning moment demands are negligible. For the Level II events, amplification of the interstory drift angle demands by severe stiffness degradation was less drastic than that reported for the Los Angeles 3-story building. Such degradation increased the median interstory drift angle by 15% for Level II events, and 70% for Level III events. The corresponding 84th percentile story drift angles increased by 30%, and 110%, respectively. Severe stiffness deterioration can increase residual drift demand by as much as 125%.

Boston, Massachusetts. For Level II events, the effects of stiffness deterioration on seismic demand for the 3-story Boston model building were generally negligible. For Level III events, severe stiffness degradation increased median and 84th percentile interstory drift demand at the lowest floor by 15% and 42%, respectively. The adverse effects on the upper-level interstory drift demands were either very small or non-existent. As before, the effect of stiffness deterioration on story shear and overturning moment demands are negligible. Therefore, we can say that stiffness deterioration has no substantial adverse effect on force demands on the 3-story buildings located in the three geographic locations considered.

The 9 Story Buildings

Los Angeles, California. Here again, the effect of stiffness deterioration on story shear and overturning moment demands are negligible. Severe stiffness degradation can increase median interstory drift angles by 25% for Level II and 60% for Level III events, respectively. The corresponding 84th percentile values are increased by as much as 50% and 110%, which are similar to the amplification factors observed for the 3-story Los Angeles building. For Level I events, severe stiffness degradation reduces the median residual interstory drift demand at the lower floors by about 5 to 25% and a small increase at the upper floors (about 10%). The reduction at the lower floors for the 84th percentile values are similar to the reduction in the median values but the amplification at the upper floors may be as much as 50%. For Level II events, severe stiffness degradation amplifies median residual interstory drift angles by about 25% at the roof and 75% at the middle floors. The ratios however, are significantly reduced at the lower floors and become 25% smaller than that of a building with no degradation. The 84th percentile amplification pattern is very different. Here amplification increases from 0% at the top floor to more than 120% at the lowermost floor. Severe stiffness degradation amplifies the Level III median and 84th percentile residual drifts by as much as 75% and 225%, respectively.

Seattle, Washington. For Level II events, severe stiffness degradation amplifies the median and 84th percentile story drift angles by about 15 to 20% and this amplification is not a strong function of the height. For Level III events, severe stiffness degradation can amplify the median and 84th interstory drift angles by 60% and 120%, respectively. Amplifications near the upper and lowermost floors are significantly larger than in the middle floors. For Level II events, severe stiffness deterioration can reduce median residual interstory drift demand by as much as 50% and the 84th percentile demand at the lower floors by as much as 20%. However, it increases 84th percentile demands at the upper floors by as much as 45%. For Level III events the effects of severe stiffness degradation on residual story drifts are much more adverse. The median values are increased by as much as 120% and the 84th percentile values by more than 200%. Stiffness deterioration does not have an appreciable adverse effect on story shear demands or overturning moment demands.

Boston, Massachusetts. Adverse effects of stiffness deterioration on this Boston model building are minimal. No adverse effect was observed in response to the Level II events. In response to Level III events the median interstory drift angles were amplified only by less than 4%. The 84th percentile values were amplified by a maximum of 11%. Interestingly enough, median and 84th percentile residual interstory drift demands for Level III events were reduced by as much as 55%. Effects of stiffness degradation on story shear and overturning moment demands were found to be negligible.

The 20 Story Buildings

Los Angeles, California. Nominal and moderate stiffness degradations tend to reduce the interstory drift angles at the upper floors and decrease them at the lower floors. Severe stiffness deterioration generally has the same effect except for the Level III 84th percentile values where the demand is also increased at the upper levels. For Level I events, amplification of the interstory drift demands due to severe stiffness degradation vary from 5% for the median values to slightly less than 20% for the 84th percentile values. Same numbers for Level II and Level III events are 20% and 45%, and 35% to more than 60%, respectively. The residual interstory drift demands are not adversely affected by nominal and moderate stiffness deterioration. This is not the case, however, for severe stiffness degradation that may increase this demand by more than 75%. As has been the case for all buildings studied so far, the adverse effects of stiffness degradation on force demands (i.e., story shears and overturning moments) are negligible.

Seattle, Washington. Effects of stiffness degradation on seismic demands for Level II events are generally minor and of little significance. The case for Level III events is very different, however, where the median and 84th percentile interstory drift angles are amplified by 50% and 150% due to severe stiffness degradation. Amplification of interstory drifts at the top floors and near the bottom is several times larger than that in the middle floors. Residual interstory drifts are affected even more adversely by severe stiffness degradation where the median and 84th percentile values are amplified by 120% and 350%. Adverse effects on the force demands are all less than 5% and hence negligible.

Boston, Massachusetts. Stiffness degradation has no effect on Level II seismic demands. For Level III events, the effects are minor except at the uppermost floors where the 84th percentile interstory drift and residual drift demands are amplified by 135% and 350%, respectively. As before, the adverse effects on the force demands are all less than 5% and hence negligible.

EFFECTS OF SLIP DETERIORATIONS

Slip deterioration did not result in collapses in any of the model buildings considered in our studies.

The Three Story Buildings

Los Angeles, California. The effect of slip deterioration on Level I interstory drift angle demands are minor. The median and 84th percentile interstory drift angles are amplified at the top floor by about 10% while there is no amplification at the lowest floor. In response to Level II ground motions the Bauschinger effect amplified the median and 84th percentile interstory drift angles by about 10% and 20%, respectively while severe slip degradation amplified the corresponding demands by 40% and 45%. Amplification of interstory drift angles by the Bauschinger effect for Level III events is less pronounced and caps out at about 15% for the median values and is less than 10%. Severe slip degradation however can magnify the drift demand by slightly more than 25% for the 84th percentile values. Magnification of median values is less at about 15%. The effects of slip deterioration on story shear and overturning moment demands were negligible.

Seattle, Washington. Slip deterioration did not produce any effects on the relative seismic demand statistics for the 3-story Seattle model building.

Boston, Massachusetts. For Level II events, the effects of slip deterioration on seismic demands for the 3-story Boston model building were generally negligible. For Level III events, severe slip degradation decreased median interstory drift demand by about 25% at the lowest floor and more than 50% at the upper two floors. The corresponding 84th percentile values were increased by about 50% at the lowest floor and decreased by about 20% at the uppermost floor. The effects of slip deterioration on story shear and overturning moment demands were negligible.

The 9 Story Buildings

Los Angeles, California. Slip degradation tended to increase interstory drift demands on the upper half of the building. For the Level I ground motions amplification of interstory drift angles is nominal and does not exceed 13% for the 84th percentile values. For Level II events story drift angle amplifications due to severe slip degradation were as large as 12% for the median values and 20% for the 84th percentile values. For Level III events the corresponding amplifications rise to 20% and 45% at the uppermost level, respectively. These amplifications, in general, are smaller than those observed for the stiffness degradation cases. Similar to the case of the 3-story building, moderate and severe slip degradations generally reduce the residual interstory drift demand. This reduction can be as much as 80% for moderate degradation and 50% to 75% for severe degradation. The effect of stiffness deterioration on story shear and overturning moment demands which have been negligible for all the cases studied so far, become more significant in response of the system with severe slip degradation to level III events. Here the 84th percentile story force and moment demands are increases by as much as 8% and 16%, respectively.

Seattle, Washington. Similar to the case of the 3-story Seattle building, slip deterioration did not produce any effects on the relative seismic demand statistics for the 9-story Seattle model building.

Boston, Massachusetts. For Level II events, slip deterioration had no effect on the seismic demands for the 9-story Boston model building. For Level III events, effects of slip degradation on the interstory drift demands were negligible. The residual drift demands reduced drastically, however, because of slip degradation. The reduction was much more pronounce for the 84th level values (between 45% to 75%) as compared to the median values (between 10% to 50%). The effects of slip deterioration on story shear and overturning moment demands were negligible.

The 20 Story Buildings

Los Angeles, California. Slip deterioration reduced the interstory drift angles at the upper floors and increased them at the lower floors. The magnitude of this effect is, however, negligible for the Level I events and minor for the Level II events. In response to Level III events, the story drift demands was amplified due to severe slip degradation by about 10% at the lower floors and reduced up to 30% at the upper floors. As with the cases of other buildings studied so far, slip deterioration tends to reduce the residual interstory drift demands, particularly at the lower and upper floors of the building. A serious exception to this rule is the case of severe slip degradation in response to the Level III events where at the uppermost floor the median and 84th percentile residual drift demands are amplified by 120% and 55%, respectively. Slip deterioration also tends to decrease story shear and overturning moment demands. The magnitude of this reduction, however, is negligible in response to Level I and Level II events but can be as much as 13% in response to Level III events. Notice, however, that this reduction is not uniform throughout the height and small amplification of force demand (up to about 5%) may be observed at the uppermost floor of the building.

Seattle, Washington. Contrary to the cases of the 3-story and 9-story Seattle buildings, the effects of slip deterioration on seismic demand imposed on the 20-story Seattle model building are considerable. Effects of slip degradation on interstory drift angles for Level II events are generally insignificant. The case for Level III events is very different, however. Here, the median and 84th percentile interstory drift angles at the top floor of the building are amplified by 45% and 70%, respectively. In addition, at the lowest few floors, severe slip degradation may increase the 84th percentile interstory drift demands by as much as 50%. Slip deterioration has little effect on interstory drift demands in response to the Level II events except at the uppermost floors for the 84th percentile values where interstory drift angles may be amplified by 15%. In response to the Level III events, the interstory drift demands are reduced at the middle floors by up to 20% and amplified at the lower and upper floors. Amplification at the lower floors is about 15% for the median values and 50% for the 84th percentile values. Amplification at the upper floors is larger and amounts to 45% (median) and 70% (84th percentile) at the uppermost floor of the building. In response to the Level II ground motions, severe slip degradation increased the median and 84th percentile residual drifts at the uppermost level by 25% and 150%, respectively. In response to Level III events severe slip has amplified the median and 84th percentile demands by as much as 80% and 375%. Effects on force demands are much less drastic and story shear and overturning moments are changed up or down generally by less than 15% with reduction usually at the lower floors and increase occurring at the upper floors.

Boston, Massachusetts. Slip degradation did not produce any effects on the response of this building to Level II ground motions. In response to Level III events the interstory drift angle demands as well as residual drift demands were amplified at the uppermost levels. Amplification of the median interstory drift demands is negligible. The 84th percentile values at these floors, however, were amplified by as much as 20%. The median and 84th percentile residual drift angles, at the uppermost floors, were amplified by 110% and 350%, respectively. The adverse effects of slip degradation on the force demands are negligible.

CONCLUSIONS

We have presented results of our investigations into the effects of various hysteretic degradation characteristics on seismic demands imposed on multistory steel moment frame buildings located in three distinct seismic zones, Los Angeles, Seattle, and Boston.

New analytical models of hysteretic behavior were presented that allow both multi-linear and smooth representation of various hysteretic characteristics. A black-box metaphor was utilized to this end so that our hysteretic models can be readily integrated into any nonlinear-capable computer program. We assessed on a consistent statistical basis the relative effect on local and global response parameters of various types of deterioration in hysteretic characteristics that might be exhibited by steel moment-resisting frames

We identified conditions where deterioration of hysteretic characteristics has either a benign or an adverse impact on system performance or reliability relative to systems without deterioration. The findings presented in this paper will be of value in assessing the need to develop beam-to-column connection details with non-deteriorating, full hysteretic loops. Procedures were developed and presented to predict important local and global seismic demand parameters for steel moment-resisting frames exhibiting various types of hysteretic behavior, accounting for the dynamic characteristics of the structure and design ground motion.

We have learned a lot during this investigation about the significance and/or lack of significance of various degradations on key seismic demand parameters. Plenty more, however, remains to be learned.

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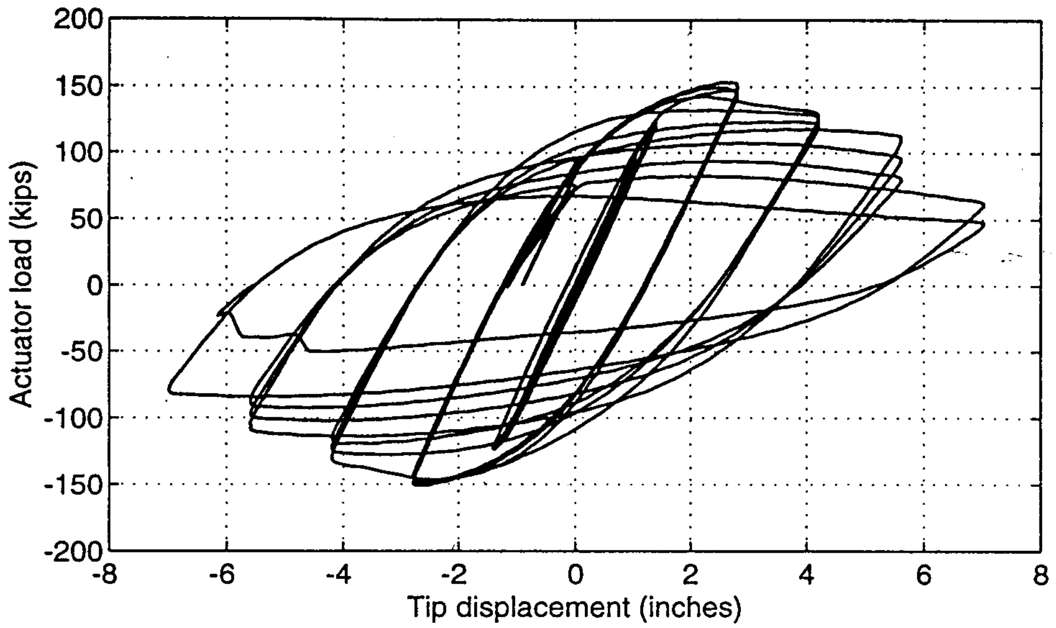
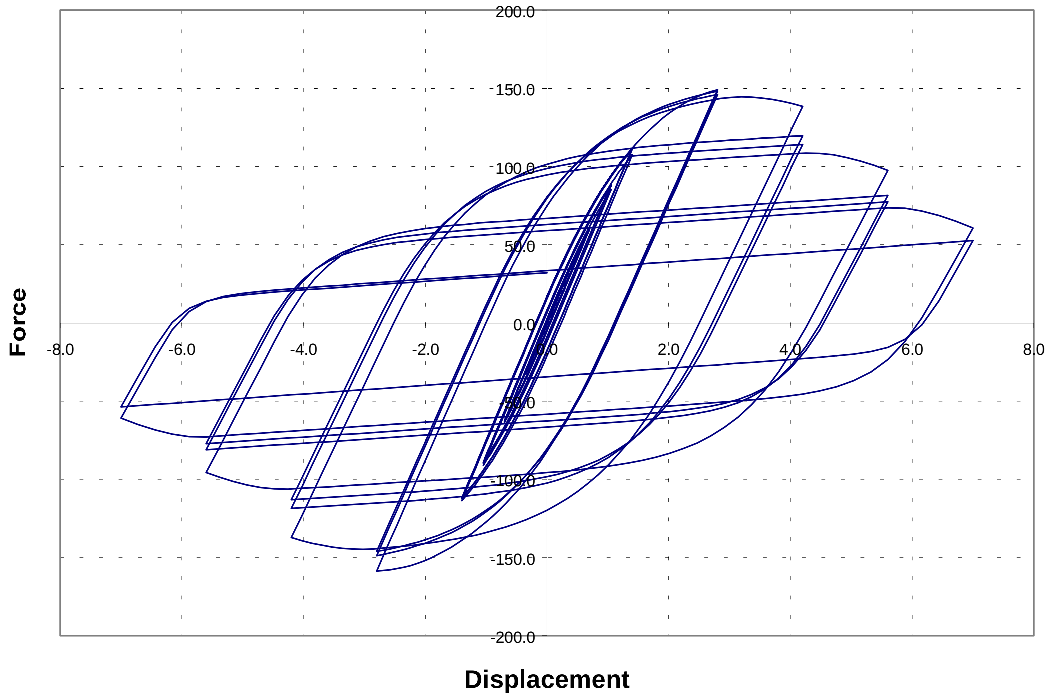


(a) Experiment



(b) Analytical [□=10, □1 = 0.5, □2 = 0.25, □ult = 9]

FIG. 1. Experimental versus Analytical loops for SAC Test No. EERC-RN2